(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 November 2001 (29.11.2001)

PCT

(10) International Publication Number
WO 01/89526 A1

(51) International Patent Classification[7]: A61K 31/44

(21) International Application Number: PCT/US01/15708

(22) International Filing Date: 16 May 2001 (16.05.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/206,364 23 May 2000 (23.05.2000) US
09/855,446 15 May 2001 (15.05.2001) US

(71) Applicant: NORTH SHORE-LONG ISLAND JEWISH RESEARCH INSTITUTE [US/US]; 350 Community Drive, Manhasset, NY 11030 (US).

(72) Inventor: TRACEY, Kevin, J.; 17 Highview Avenue, Old Greenwich, CT 06870 (US).

(74) Agents: ARNOLD, Craig, J. et al.; Amster, Rothstein & Ebenstein, 90 Park Avenue, New York, NY 10016 (US).

(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*
— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments*

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

WO 01/89526 A1

(54) Title: INHIBITION OF INFLAMMATORY CYTOKINE PRODUCTION BY CHOLINERGIC AGONISTS AND VAGUS NERVE STIMULATION

(57) Abstract: A method of inhibiting the release of a proinflammatory cytokine in a cell is disclosed. The method comprises treating the cell with a cholinergic agonist. The method is useful in patients at risk for, or suffering from, a condition mediated by an inflammatory cytokine cascade, for example endotoxic shock. The cholinergic agonist treatment can be effected by stimulation of an efferent vagus nerve fiber, or the entire vagus nerve.

INHIBITION OF INFLAMMATORY CYTOKINE PRODUCTION BY CHOLINERGIC AGONISTS AND VAGUS NERVE STIMULATION

Background of the Invention

(1) Field of the Invention

The present invention generally relates to methods of reducing inflammation. More specifically, the invention relates to methods for reducing inflammation caused by proinflammatory cytokines or an inflammatory cytokine cascade.

(2) Description of the Related Art

Vertebrates achieve internal homeostasis during infection or injury by balancing the activities of proinflammatory and anti-inflammatory pathways. However, in many disease conditions, this internal homeostasis becomes out of balance. For example, endotoxin (lipopolysaccharide, LPS) produced by all Gram-negative bacteria activates macrophages to release cytokines that are potentially lethal (44; 10; 47; 31).

Inflammation and other deleterious conditions (such as septic shock caused by endotoxin exposure) are often induced by proinflammatory cytokines, such as tumor necrosis factor (TNF; also known as TNFα or cachectin), interleukin (IL)-1α, IL-1β, IL-6, IL-8, IL-18, interferonγ, platelet-activating factor (PAF), macrophage migration inhibitory factor (MIF), and other compounds (42). Certain other compounds, for example high mobility group protein 1 (HMG-1), are induced during various conditions such as sepsis and can also serve as proinflammatory cytokines (57). These proinflammatory cytokines are produced by several different cell types, most importantly immune cells (for example monocytes, macrophages and neutrophils), but also non-immune cells such as fibroblasts, osteoblasts, smooth muscle cells, epithelial cells, and neurons (56). Proinflammatory cytokines contribute to various

disorders, notably sepsis, through their release during an inflammatory cytokine cascade.

Inflammatory cytokine cascades contribute to deleterious characteristics, including inflammation and apoptosis (32), of numerous disorders. Included are disorders characterized by both localized and systemic reactions, including, without limitation, diseases involving the gastrointestinal tract and associated tissues (such as appendicitis, peptic, gastric and duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, coeliac disease, cholecystitis, hepatitis, Crohn's disease, enteritis, and Whipple's disease); systemic or local inflammatory diseases and conditions (such as asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, and sarcoidosis); diseases involving the urogential system and associated tissues (such as septic abortion, epididymitis, vaginitis, prostatitis and urethritis); diseases involving the respiratory system and associated tissues (such as bronchitis, emphysema, rhinitis, cystic fibrosis, adult respiratory distress syndrome, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, and sinusitis); diseases arising from infection by various viruses (such as influenza, respiratory syncytial virus, HIV, hepatitis B virus, hepatitis C virus and herpes), bacteria (such as disseminated bacteremia, Dengue fever), fungi (such as candidiasis) and protozoal and multicellular parasites (such as malaria, filariasis, amebiasis, and hydatid cysts); dermatological diseases and conditions of the skin (such as burns, dermatitis, dermatomyositis, sunburn, urticaria warts, and wheals); diseases involving the cardiovascular system and associated tissues (such as vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, congestive heart failure, periarteritis nodosa, and rheumatic fever); diseases involving the central or peripheral nervous system and associated tissues (such as Alzheimer's

disease, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, and uveitis); diseases of the bones, joints, muscles and connective tissues (such as the various arthritides and arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, and synovitis); other autoimmune and inflammatory disorders (such as myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, and Retier's syndrome); as well as various cancers, tumors and proliferative disorders (such as Hodgkins disease); and, in any case the inflammatory or immune host response to any primary disease (13; 55; 30; 20; 33; 25; 18; 27; 48; 24; 7; 9; 4; 3; 12; 8; 19; 15; 23; 22; 49; 34).

Mammals respond to inflammation caused by inflammatory cytokine cascades in part though central nervous system regulation. This response has been characterized in detail with respect to systemic humoral response mechanisms during inflammatory responses to endotoxin (2; 54; 21; 28). In one set of responses, afferent vagus nerve fibers are activated by endotoxin or cytokines, stimulating the release of humoral anti-inflammatory responses through glucocorticoid hormone release (51; 41; 39). Previous work elucidated a role for vagus nerve signaling as a critical component in the afferent loop that modulates the adrenocorticotropin and fever responses to systemic endotoxemia and cytokinemia (14; 11; 52; 35). However, comparatively little is known about the role of efferent neural pathways that can modulate inflammation.

Efferent vagus nerve signaling has been implicated in facilitating lymphocyte release from thymus via a nicotinic acetylcholine receptor response (1). Clinical studies have also indicated that nicotine administration can be effective for treating some cases of inflammatory bowel disease (17; 36), and that proinflammatory cytokine levels are significantly decreased in the colonic mucosa of smokers with inflammatory bowel disease (40). However, none of

these findings would suggest that cholinergic agonists can inhibit an inflammatory cytokine cascade, particularly those mediated by macrophages. Also, there is no suggestion in the literature that efferent vagus nerve stimulation is effective in inhibiting these cascades.

Summary of the Invention

Accordingly, the inventor has succeeded in discovering that cholinergic agonists can inhibit the release of proinflammatory cytokines from a mammalian cell, either *in vitro* or *in vivo*. This inhibitory effect is useful for inhibiting inflammatory cytokine cascades that mediate many disease conditions. Furthermore, cholinergic agonist treatment *in vivo* can be effected to inhibit either local or systemic inflammatory cytokine cascades by stimulating efferent vagus nerves.

Thus, one embodiment of the present invention is directed to a method of inhibiting the release of a proinflammatory cytokine from a mammalian cell. The method comprises treating the cell with a cholinergic agonist in an amount sufficient to decrease the amount of the proinflammatory cytokine that is released from the cell. In preferred embodiments, the cell is a macrophage. Preferably, the proinflammatory cytokine is tumor necrosis factor (TNF), interleukin (IL)-1β, IL-6, IL-18 or HMG-1, most preferably TNF. In preferred embodiments, the cholinergic agonist is acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, or levamisole. In other preferred embodiments, the cell is in a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade, preferably appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma,

granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis, cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza, respiratory syncytial virus infection, herpes infection, HIV infection, hepatitis B virus infection, hepatitis C virus infection, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, coeliac disease, congestive heart failure, adult respiratory distress syndrome, Alzheimer's disease, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, or Hodgkins disease. In more preferred embodiments, the condition is appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection or graft-versus-host disease. In the most preferred embodiments, the condition is endotoxic shock. In some embodiments, the cholinergic agonist treatment is effected by stimulating efferent vagus nerve activity sufficient to inhibit the inflammatory cytokine cascade. Preferably, the

efferent vagus nerve activity is stimulated electrically. The efferent vagus nerve can be stimulated without stimulating the afferent vagus nerve. Vagus nerve ganglions or postganglionic neurons can also be stimulated. Additionally, peripheral tissues or organs that are served by the vagus nerve can also be stimulated directly.

The present invention is also directed to a method of inhibiting an inflammatory cytokine cascade in a patient. The method comprises treating the patient with a cholinergic agonist in an amount sufficient to inhibit the inflammatory cytokine cascade, wherein the patient is suffering from, or at risk for, a condition mediated by the inflammatory cytokine cascade. The cholinergic agonist is preferably acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, or levamisole, and the condition is preferably appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis, cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza, respiratory syncytial virus infection, herpes infection, HIV infection, hepatitis B virus infection, hepatitis C virus infection, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, meningitis, encephalitis, multiple sclerosis, cerebral

infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, or Hodgkins disease. In more preferred embodiments, the condition is appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection or graft-versus-host disease. In the most preferred embodiments, the condition is endotoxic shock. The cholinergic agonist treatment can be effected by stimulating efferent vagus nerve activity, preferably electrically.

In additional embodiments, the present invention is directed to a method for treating a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade. The method comprises stimulating efferent vagus nerve activity of the patient sufficient to inhibit the inflammatory cytokine cascade. Preferred methods of stimulation and preferred conditions are as with the previously described methods.

In still other embodiments, the present invention is directed to a method for attenuation of a systemic inflammatory response to endotoxin in a patient. The method comprises stimulating efferent vagus nerve activity of the patient sufficient to inhibit an inflammatory cytokine cascade.

The present invention is additionally directed to a method for determining whether a compound is a cholinergic agonist. The method

comprises determining whether the compound inhibits the release of a proinflammatory cytokine from a mammalian cell. In preferred embodiments the cell is a macrophage and the proinflammatory cytokine is TNF.

Brief Description of the Drawings

Figure 1 is a graph summarizing experimental results showing that cholinergic agonists inhibit release of TNF from human macrophage cultures in a dose-dependent manner. Acetylcholine (ACh), muscarine, or nicotine was added to human macrophage cultures at the concentrations indicated, followed by LPS addition for 4 hours. TNF concentration was then determined.

Figure 2 shows autoradiographs of TNF or GADPH mRNA from LPS-stimulated human macrophages treated with acetylcholine (ACh), nicotine (Nic) or muscarine (Mus), or no cholinergic agonist, which demonstrate that cholinergic agonists do not reduce LPS-stimulated TNF mRNA levels in macrophages.

Figure 3 shows micrographs of human macrophages stained with TNF antibodies demonstrating the effect of LPS and/or acetylcholine (ACh) treatment on TNF presence in the cells.

Figure 4 is a graph summarizing experimental results showing that α-conotoxin (α-CTX), but not atropine (ATR), reverses the inhibitory effect of acetylcholine (ACh)-mediated inhibition of TNF in human macrophages.

Figure 5 is a graph summarizing experimental results showing that acetylcholine inhibits IL-1β release from human macrophages in a dose-dependent manner.

Figure 6 is a graph summarizing experimental results showing that acetylcholine inhibits IL-6 release from human macrophages in a dose-dependent manner.

Figure 7 is a graph summarizing experimental results showing that acetylcholine inhibits IL-18 release from human macrophages in a dose-dependent manner.

Figure 8 is a graph summarizing experimental results showing that acetylcholine does not inhibit IL-10 release from human macrophages.

Figure 9 is a graph summarizing experimental results showing that vagus nerve stimulation (STIM) after vagotomy (VGX) causes a decrease in circulating levels of TNF during endotoxemia induced by LPS.

Figure 10 is a graph summarizing experimental results showing that vagus nerve stimulation (STIM) after vagotomy (VGX) causes a decrease in levels of TNF in the liver during endotoxemia induced by LPS.

Figure 11 is a graph summarizing experimental results showing that vagus nerve stimulation (STIM) after vagotomy (VGX) attenuates the development of hypotension (shock), as measured by mean arterial blood pressure (MABP), in rats exposed to lethal doses of endotoxin.

Figure 12 is a graph summarizing experimental results showing that intact vagus nerve stimulation at 1V and 5V attenuates the development of shock in rats exposed to lethal doses of endotoxin.

Figure 13 is a graph summarizing experimental results showing that intact vagus nerve stimulation at 1V and 5V causes an increase in heart rate in rats exposed to lethal doses of endotoxin.

Figure 14 is a graph summarizing experimental results showing that intact left vagus nerve stimulation at 1V stabilized blood pressure more effectively than intact right vagus nerve stimulation, in rats exposed to lethal doses of endotoxin.

Figure 15 is a western blot and graph of experimental results showing that addition of nicotine to RAW 264.7 macrophage-like cells inhibits the production of HMG-1 by the cells.

Detailed Description of the Invention

The practice of the present invention will employ, unless otherwise indicated, conventional techniques of cell culture, molecular biology, microbiology, cell biology, and immunology, which are well within the skill of

the art. Such techniques are fully explained in the literature. See, e.g., Sambrook et al., 1989, "Molecular Cloning: A Laboratory Manual", Cold Spring Harbor Laboratory Press; Ausubel et al. (1995), "Short Protocols in Molecular Biology", John Wiley and Sons; Methods in Enzymology (several volumes); Methods in Cell Biology (several volumes), and Methods in Molecular Biology (several volumes).

The present invention is based on the discovery that treatment of a proinflammatory cytokine-producing cell with a cholinergic agonist attenuates the release of proinflammatory cytokines from that cell, and that this attenuation process can be utilized in treatments for disorders mediated by an inflammatory cytokine cascade (5-6). It has further been discovered that stimulation of efferent vagus nerve fibers releases sufficient acetylcholine to stop a systemic inflammatory cytokine cascade, as occurs in endotoxic shock (5), or a localized inflammatory cytokine cascade (6). The efferent vagus nerve stimulation can also inhibit a localized inflammatory cytokine cascade in tissues and organs that are served by efferent vagus nerve fibers.

Accordingly, in some embodiments the present invention is directed to methods of inhibiting the release of a proinflammatory cytokine from a mammalian cell.The methods comprise treating the cell with a cholinergic agonist in an amount sufficient to decrease the amount of the proinflammatory cytokine released from the cell.

As used herein, a cytokine is a soluble protein or peptide which is naturally produced by mammalian cells and which act *in vivo* as humoral regulators at micro- to picomolar concentrations. Cytokines can, either under normal or pathological conditions, modulate the functional activities of individual cells and tissues. A proinflammatory cytokine is a cytokine that is capable of causing any of the following physiological reactions associated with inflammation: vasodialation, hyperemia, increased permeability of vessels with associated edema, accumulation of granulocytes and mononuclear phagocytes, or deposition of fibrin. In some cases, the proinflammatory cytokine can also

cause apoptosis, such as in chronic heart failure, where TNF has been shown to stimulate cardiomyocyte apoptosis (32; 45). Nonlimiting examples of proinflammatory cytokines are tumor necrosis factor (TNF), interleukin (IL)-1α, IL-1β, IL-6, IL-8, IL-18, interferonγ, HMG-1, platelet-activating factor (PAF), and macrophage migration inhibitory factor (MIF). In preferred embodiments of the invention, the proinflammatory cytokine that is inhibited by cholinergic agonist treatment is TNF, an IL-1, IL-6 or IL-18, because these cytokines are produced by macrophages and mediate deleterious conditions for many important disorders, for example endotoxic shock, asthma, rheumatoid arthritis, inflammatory bile disease, heart failure, and allograft rejection. In most preferred embodiments, the proinflammatory cytokine is TNF.

Proinflammatory cytokines are to be distinguished from anti-inflammatory cytokines, such as IL-4, IL-10, and IL-13, which are not mediators of inflammation. In preferred embodiments, release of anti-inflammatory cytokines is not inhibited by cholinergic agonists.

In many instances, proinflammatory cytokines are produced in an inflammatory cytokine cascade, defined herein as an *in vivo* release of at least one proinflammatory cytokine in a mammal, wherein the cytokine release affects a physiological condition of the mammal. Thus, an inflammatory cytokine cascade is inhibited in embodiments of the invention where proinflammatory cytokine release causes a deleterious physiological condition.

Any mammalian cell that produces proinflammatory cytokines are useful for the practice of the invention. Nonlimiting examples are monocytes, macrophages, neutrophils, epithelial cells, osteoblasts, fibroblasts, smooth muscle cells, and neurons. In preferred embodiments, the cell is a macrophage.

As used herein, a cholinergic agonist is a compound that binds to cells expressing cholinergic receptor activity. The skilled artisan can determine whether any particular compound is a cholinergic agonist by any of several well known methods.

When referring to the effect of the cholinergic agonist on release of proinflammatory cytokines or an inflammatory cytokine cascade, or the effect of vagus nerve stimulation on an inflammatory cytokine cascade, the use of the terms "inhibit" or "decrease" encompasses at least a small but measurable reduction in proinflammatory cytokine release. In preferred embodiments, the release of the proinflammatory cytokine is inhibited by at least 20% over non-treated controls; in more preferred embodiments, the inhibition is at least 50%; in still more preferred embodiments, the inhibition is at least 70%, and in the most preferred embodiments, the inhibition is at least 80%. Such reductions in proinflammatory cytokine release are capable of reducing the deleterious effects of an inflammatory cytokine cascade in *in vivo* embodiments.

Any cholinergic agonist, now known or later discovered, would be expected to inhibit the release of proinflammatory cytokines from mammalian cells. In preferred embodiments, the cholinergic agonist is not otherwise toxic to the cell at useful concentrations. In more preferred embodiments, the cholinergic agonist has been used therapeutically *in vivo* or is naturally produced by mammalian cells. Nonlimiting examples include acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, and levamisole. In most preferred *in vitro* embodiments, the cholinergic agonist is acetylcholine, nicotine, or muscarine. In *in vivo* embodiments, acetylcholine is not preferred because the compound would be expected to be inactivated very quickly due to the widespread occurrence of acetylcholinesterase in tissues.

The present invention is useful for studying cells in culture, for example studying the effect of inflammatory cytokine release on the biology of macrophages, or for testing compounds for cholinergic agonist activity. However, *in vivo* applications make up many of the preferred embodiments. In those embodiments, the cell is in a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade. As used herein, a patient can be any mammal. However, in preferred embodiments, the patient is a human.

The treatment of any condition mediated by an inflammatory cytokine cascade is within the scope of the invention. In preferred embodiments, the condition is one where the inflammatory cytokine cascade is effected through release of proinflammatory cytokines from a macrophage. The condition can be one where the inflammatory cytokine cascade causes a systemic reaction, such as with septic shock. Alternatively, the condition can be mediated by a localized inflammatory cytokine cascade, as in rheumatoid arthritis. Nonlimiting examples of conditions which can be usefully treated using the present invention include those conditions enumerated in the background section of this specification. Preferably, the condition is appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis, cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza, respiratory syncytial virus, herpes, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus,

Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, or Hodgkins disease. In more preferred embodiments, the condition is appendicitis, peptic, gastric or duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute or ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection or graft-versus-host disease. In the most preferred embodiments, the condition is endotoxic shock.

The route of administration of the cholinergic agonist depends on the condition to be treated. For example, intravenous injection may be preferred for treatment of a systemic disorder such as septic shock, and oral administration may be preferred to treat a gastrointestinal disorder such as a gastric ulcer. The route of administration and the dosage of the cholinergic agonist to be administered can be determined by the skilled artisan without undue experimentation in conjunction with standard dose-response studies. Relevant circumstances to be considered in making those determinations include the condition or conditions to be treated, the choice of composition to be administered, the age, weight, and response of the individual patient, and the severity of the patient's symptoms. Thus, depending on the condition, the cholinergic agonist can be administered orally, parenterally, intranasally, vaginally, rectally, lingually, sublingually, bucally, intrabuccaly and transdermally to the patient.

Accordingly, cholinergic agonist compositions designed for oral, lingual, sublingual, buccal and intrabuccal administration can be made without undue experimentation by means well known in the art, for example with an inert

diluent or with an edible carrier. The compositions may be enclosed in gelatin capsules or compressed into tablets. For the purpose of oral therapeutic administration, the pharmaceutical compositions of the present invention may be incorporated with excipients and used in the form of tablets, troches, capsules, elixirs, suspensions, syrups, wafers, chewing gums and the like.

Tablets, pills, capsules, troches and the like may also contain binders, recipients, disintegrating agent, lubricants, sweetening agents, and flavoring agents. Some examples of binders include microcrystalline cellulose, gum tragacanth or gelatin. Examples of excipients include starch or lactose. Some examples of disintegrating agents include alginic acid, corn starch and the like. Examples of lubricants include magnesium stearate or potassium stearate. An example of a glidant is colloidal silicon dioxide. Some examples of sweetening agents include sucrose, saccharin and the like. Examples of flavoring agents include peppermint, methyl salicylate, orange flavoring and the like. Materials used in preparing these various compositions should be pharmaceutically pure and nontoxic in the amounts used.

Cholinergic agonist compositions of the present invention can easily be administered parenterally such as for example, by intravenous, intramuscular, intrathecal or subcutaneous injection. Parenteral administration can be accomplished by incorporating the cholinergic agonist compositions of the present invention into a solution or suspension. Such solutions or suspensions may also include sterile diluents such as water for injection, saline solution, fixed oils, polyethylene glycols, glycerine, propylene glycol or other synthetic solvents. Parenteral formulations may also include antibacterial agents such as for example, benzyl alcohol or methyl parabens, antioxidants such as for example, ascorbic acid or sodium bisulfite and chelating agents such as EDTA. Buffers such as acetates, citrates or phosphates and agents for the adjustment of tonicity such as sodium chloride or dextrose may also be added. The parenteral preparation can be enclosed in ampules, disposable syringes or multiple dose vials made of glass or plastic.

Rectal administration includes administering the pharmaceutical compositions into the rectum or large intestine. This can be accomplished using suppositories or enemas. Suppository formulations can easily be made by methods known in the art. For example, suppository formulations can be prepared by heating glycerin to about 120° C., dissolving the cholinergic agonist in the glycerin, mixing the heated glycerin after which purified water may be added, and pouring the hot mixture into a suppository mold.

Transdermal administration includes percutaneous absorption of the cholinergic agonist through the skin. Transdermal formulations include patches (such as the well-known nicotine patch), ointments, creams, gels, salves and the like.

The present invention includes nasally administering to the mammal a therapeutically effective amount of the cholinergic agonist. As used herein, nasally administering or nasal administration includes administering the cholinergic agonist to the mucous membranes of the nasal passage or nasal cavity of the patient. As used herein, pharmaceutical compositions for nasal administration of a cholinergic agonist include therapeutically effective amounts of the agonist prepared by well-known methods to be administered, for example, as a nasal spray, nasal drop, suspension, gel, ointment, cream or powder. Administration of the cholinergic agonist may also take place using a nasal tampon or nasal sponge.

In accordance with the present invention, it has also been discovered that the cholinergic agonist can be administered to the patient in the form of acetylcholine by stimulating efferent vagus nerve fibers. As is well known, efferent vagus nerve fibers secrete acetylcholine upon stimulation. Such stimulation releases sufficient acetylcholine to be effective in inhibiting a systemic inflammatory cytokine cascade as well as a localized inflammatory cytokine cascade in a tissue or organ that is served by efferent branches of the vagus nerve, including the pharynx, the larynx, the esophagus, the heart, the

lungs, the stomach, the pancreas, the spleen, the kidneys, the adrenal glands, the small and large intestine, the colon, and the liver.

The effect of vagus nerve stimulation on the inhibition of inflammatory cytokine cascades is not necessarily limited to that caused by acetylcholine release. The scope of the invention also encompasses any other mechanism that is partly or wholly responsible for the inhibition of inflammatory cytokine cascades by vagus nerve stimulation. Nonlimiting examples include the release of serotonin agonists or stimulation of other neurotransmitters.

As used herein, the vagus nerve is used in its broadest sense, and includes any nerves that branch off from the main vagus nerve, as well as ganglions or postganglionic neurons that are connected to the vagus nerve. The vagus nerve is also known in the art as the parasympathetic nervous system and its branches, and the cholinergic nerve.

The efferent vagus nerve fibers can be stimulated by any means. Nonlimiting examples include: mechanical means such as a needle, ultrasound, or vibration; any electromagnetic radiation such as infrared, visible or ultraviolet light; heat, or any other energy source. In preferred embodiments, the vagus nerve is stimulated electrically, using for example a commercial vagus nerve stimulator such as the Cyberonics NCP®, or an electric probe. The efferent vagus nerve can be stimulated by stimulating the entire vagus nerve (i.e., both the afferent and efferent nerves), or by isolating efferent nerves and stimulating them directly. The latter method can be accomplished by separating the afferent from the efferent fibers in an area of the nerve where both types of fibers are present. Alternatively, the efferent fiber is stimulated where no afferent fibers are present, for example close to the target organ served by the efferent fibers. The efferent fibers can also be stimulated by stimulating the target organ directly, e.g., electrically, thus stimulating the efferent fibers that serve that organ. In other embodiments, the ganglion or postganglionic neurons of the vagus nerve can be stimulated. The vagus nerve can also be cut and the

distal end can be stimulated, thus only stimulating efferent vagus nerve fibers (see, e.g., Example 2).

The amount of stimulation useful to inhibit an inflammatory cytokine cascade can be determined by the skilled artisan without undue experimentation for any condition to be treated. To inhibit a systemic inflammatory cytokine cascade, as induced with endotoxin, constant voltage stimuli of 1 to 5 V, at 2 ms and 1 Hz, for 10 min. before exposure and 10 min. after exposure, will inhibit the systemic inflammatory cytokine cascade sufficiently to prevent death of the subject by endotoxic shock (see Examples 2 and 3).

In other embodiments, the invention is directed to methods of inhibiting an inflammatory cytokine cascade in a patient. The methods comprise treating the patient with a cholinergic agonist in an amount sufficient to inhibit the inflammatory cytokine cascade. In preferred embodiments, the patient is suffering from, or at risk for, a condition mediated by the inflammatory cytokine cascade.

Cholinergic agonists useful for these embodiments have been previously discussed and include acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, and levamisole. Also as previously discussed, acetylcholine can be administered by stimulating efferent vagus nerve fibers.

In additional embodiments, the present invention is directed to a method for treating a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade. The method comprises stimulating efferent vagus nerve activity sufficient to inhibit the inflammatory cytokine cascade. Methods for stimulating efferent vagus nerve fibers have been previously discussed.

The present invention is also directed to methods for determining whether a compound is a cholinergic agonist. The method comprises determining whether the compound inhibits the release of a proinflammatory cytokine from a mammalian cell.

For this method, the cell can be any cell that can be induced to produce a proinflammatory cytokine. In preferred embodiments, the cell is an immune cell, for example macrophages, monocytes, or neutrophils. In the most preferred embodiments, the cell is a macrophage.

The proinflammatory cytokine to be measured for inhibition can be any proinflammatory cytokine that can be induced to be released from the cell. In preferred embodiments, the cytokine is TNF. Evaluation of the inhibition of cytokine production can be by any means known, including quantitation of the cytokine (e.g., with ELISA), or by bioassay, (e.g. determining whether proinflammatory cytokine activity is reduced).

Preferred embodiments of the invention are described in the following examples. Other embodiments within the scope of the claims herein will be apparent to one skilled in the art from consideration of the specification or practice of the invention as disclosed herein. It is intended that the specification, together with the examples, be considered exemplary only, with the scope and spirit of the invention being indicated by the claims which follow the examples.

Example 1

Cholinergic Agonists Inhibit Release of Proinflammatory Cytokines from Macrophages.

1. Materials and Methods

Human macrophage cultures were prepared as follows. Buffy coats were collected from the blood of healthy individual donors to the Long Island Blood Bank Services (Melville, NY). Primary blood mononuclear cells were isolated by density-gradient centrifugation through Ficoll/Hypaque (Pharmacia, NJ), suspended (8×10^6 cells/ml) in RPMI 1640 medium supplemented with 10% heat inactivated human serum (Gemini Bio-Products, Inc., Calabasas, CA), and seeded in flasks (PRIMARIA; Beckton and Dickinson Labware, Franklin Lakes, NJ). After incubation for 2 hours at 37° C, adherent cells were washed

extensively, treated briefly with 10 mM EDTA, detached, resuspended (10^6 cells/ml) in RPMI medium (10% human serum), supplemented with human macrophage colony stimulating factor (MCSF; Sigma Chemical Co., St. Louis, MO; 2 ng/ml), and seeded onto 24-well tissue culture plates (PRIMARIA; Falcon) (10^6 cells/well). Cells were allowed to differentiate for 7 days in the presence of MCSF. On day 7 the cells were washed 3 times with 1x Dulbecco's phosphate buffered saline (PBS, GibcoBRL, Life Technologies, Rockville, MD), fresh medium devoid of MCSF was added, and experiments performed as indicated.

RNase protection assays were performed as follows. Total RNA was isolated from cultured cells by using TRIzol reagent (GIBCO BRL, Rockville, MD) following the manufacturer's instructions, and electrophoresed on 1.2% agarose/17% formaldehyde gel for verification of the integrity of the RNA samples. The RNase protection assay was conducted using a kit obtained from PharMingen (San Diego, CA). The anti-sense RNA probe set (hck-3) was labeled with [a-^{32}P] UTP (Sp. Act. 800 Ci/mmol, Amersham, Arlington Heights, IL) using T7 RNA polymerase. Molecular weight markers were prepared by using pBR-322 plasmid DNA digested with MSP I (New England Bio Labs, Beverly, MA) and end-labeled using [a-^{32}P] dCTP (Sp. Act. 800 Ci/mmol, Amersham, Arlington Heights, IL) with Klenow enzyme (Strategene, La Jolla, CA).

TNF immunohistochemistry was performed as follows. Human macrophages were differentiated as described above, and grown on glass chamber slides (Nunc, Naperville, IL). Slides were incubated in a blocking solution (1% BSA, 5% normal goat serum, 0.3% Triton X-100 in PBS) for 1 hour at room temperature and then incubated for 24 hours at 4° C with a primary mouse anti-human TNF monoclonal antibody (Genzyme, Cambridge, MA) diluted 1:100 in PBS containing 0.3% Triton X-100, 0.1% BSA, and 3% normal goat serum. Washed sections were incubated for 2 hours with secondary biotinylated anti-mouse IgG (1:200, Vector Laboratories, Inc., Burlingame, CA).

The reaction product was visualized with 0.003% hydrogen peroxide and 0.05% 3,3'-diaminobenzidine tetrahydrochloride as a chromogen. Negative controls were incubated in the absence of primary antibodies (not shown). Slides were analyzed on a light microscope (Olympus BX60, Japan) using a MetaMorth Imaging System (Universal Imaging Co., West Chester, PA).

2. Results

Primary human macrophage cultures were established by incubating human peripheral blood mononuclear cells in the presence of macrophage colony stimulating factor (MCSF; Sigma Chemical Co., St. Louis, MO). These cells were used in experiments to determine the effects of cholinergic agonists on TNF levels in macrophage cultures conditioned by exposure to LPS for 4 hours (Figure 1). In those experiments, acetylcholine chloride (ACh; Sigma Chemical Co., St. Louis, MO) was added to human macrophage cultures at the indicated concentrations (squares) in the presence of the acetylcholinesterase inhibitor pyridostigmine bromide (1 mM, Sigma Chemical Co., St. Louis, MO). Muscarine (triangles) and nicotine (circles) (Sigma Chemical Co., St. Louis, MO) were added in the concentrations indicated (Figure 1). LPS was added five minutes later (100 ng/ml), and conditioned supernatants collected after 4 hours of stimulation for subsequent analysis by TNF enzyme-linked immunosorbent assay (ELISA). All the experimental conditions were performed in triplicate. Data from nine separate macrophage preparations are shown as Mean $\pm$ SEM; n=9.

As shown in Figure 1, acetylcholine, nicotine, and muscarine all inhibited TNF release in a dose dependent manner. Comparable inhibition of TNF release by acetylcholine was observed in macrophage culture media conditioned by exposure to LPS for 20 hours (not shown), indicating that the inhibitory effect of acetylcholine on TNF did not merely delay the onset of the TNF response. Inhibition of TNF was also observed in macrophage cultures treated with carbachol, a chemically distinct cholinergic agonist (not shown).

The molecular mechanism of TNF inhibition was investigated by measuring TNF mRNA levels in an RNase protection assay. In those experiments (Figure 2), macrophages were incubated in the presence of ACh (100 μM), muscarine (Mus, 100 μM), nicotine (Nic, 100 μM) or medium alone for 5 minutes followed by 2 hour exposure to LPS (100 ng/ml). ACh was added with pyridostigmine bromide (1 mM). Control wells were incubated with medium alone for 2 hours. Expression of the GAPDH gene product was measured to control for mRNA loading.

TNF mRNA levels in acetylcholine-treated, LPS-stimulated macrophages did not decrease as compared to vehicle-treated, LPS-stimulated macrophages, even when acetylcholine was added in concentrations that inhibited TNF protein release (Figure 2). This indicates that acetylcholine suppresses TNF release through a post-transcriptional mechanism.

To determine whether acetylcholine inhibited macrophage TNF synthesis or macrophage TNF release, monoclonal anti-TNF antibodies were used to label cell-associated TNF in human macrophage cultures. In those experiments (Figure 3), cells were exposed to either ACh (100 μM), either alone or in the presence of pyridostigmine bromide (1 mM), five minutes before LPS (100 ng/ml) treatment. Two hours later the cells were fixed in buffered 10% formalin and subjected to immunocytochemical analysis using primary mouse anti-hTNF monoclonal antibodies as described in Materials and Methods.

Those experiments established that acetylcholine significantly attenuated the appearance of LPS-stimulated TNF immunoreactivity in macrophages (Figure 3). Considered together, these results indicate that the inhibitory effect of acetylcholine on human macrophage TNF production occurs through the post-transcriptional suppression of TNF protein synthesis, or possibly through an increased rate of degradation of intracellular TNF (Figure 3).

Previous work indicated that peripheral blood mononuclear cells express nicotinic and muscarinic acetylcholine receptors (37-38; 53). To define pharmacologically the type of macrophage cholinergic receptor activities

involved in modulating the TNF response, the results in Figure 1 were further analyzed. Nicotine significantly inhibited TNF release in a dose-dependent manner; the effective concentration of nicotine that inhibited 50% of the TNF response ($E.C._{50}$) was estimated to be 8.3 ± 7.1 nM (n = 9). This $E.C._{50}$ for nicotine compared favorably with the $E.C._{50}$ for acetylcholine-mediated inhibition of TNF (acetylcholine $E.C._{50} = 20.2 \pm 8.7$ nM, n = 9). Muscarine also significantly inhibited TNF release, although it was a much less effective inhibitor of macrophage TNF as compared to either acetylcholine or nicotine (muscarine $E.C._{50} = 42.4 \pm 18.6$ mM, n = 9; $P<0.01$ vs nicotine or acetylcholine).

To establish whether acetylcholine inhibited TNF primarily through the activity of nicotinic or muscarinic acetylcholine receptors, the specific muscarinic antagonist, atropine, was added to LPS-stimulated macrophage cultures that were co-treated with acetylcholine (Figure 4). I also addressed whether the nicotinic acetylcholine receptor activity that mediated inhibition of TNF was a-bungarotoxin-sensitive or a-bungarotoxin-insensitive (Figure 4). Conditions for macrophage culture and TNF assays were as previously described. Atropine (striped bars) (1 mM; Sigma Chemical Co., St. Louis, MO) or α-conotoxin (black bars) (0.1, 0.01 mM; Oncogene Research Products, Cambridge, MA) were added to macrophage cultures 5 minutes prior to acetylcholine (10 μM) and LPS (100 ng/ml). Data shown are Mean ± SEM of 3 separate experiments using different macrophages prepared from separate donors.

Addition of atropine, even in concentrations as high as 1 mM, failed to restore TNF release in acetylcholine-treated macrophage cultures (Figure 4). Note that Acetylcholine inhibited TNF release by 80%, but this was not reversed by atropine. However, addition of α-conotoxin to acetylcholine-treated LPS-stimulated macrophage cultures significantly reversed the inhibitory effect of acetylcholine in a dose dependent manner (Figure 4). (**$P<0.005$ vs ACh; *$P<0.05$ vs ACh). Neither atropine nor α-conotoxin altered TNF production in

vehicle-treated cultures (not shown). Considered together, these data provide evidence that the inhibitory effect of acetylcholine on the LPS-induced TNF response in human macrophage cultures is mediated primarily by α-bungarotoxin-sensitive, nicotinic acetylcholine receptors. Acetylcholine levels in mammalian tissues can reach the millimolar range (50); however so, it is possible that both the nicotinic and muscarinic macrophage acetylcholine receptor activities described here participate in the inhibition of macrophage TNF synthesis *in vivo*.

To assess specificity, the release of other macrophage-derived cytokines was measured in LPS-stimulated macrophage cultures treated with acetylcholine. In those experiments, human macrophage cultures were incubated with ACh at the indicated concentrations in the presence of pyridostigmine bromide (1 mM) and LPS (100 ng/ml) for 20 hours. IL-1β (Figure 5), IL-6 (Figure 6) and IL-10 (Figure 8) levels were measured in media using commercially available ELISA kits (R&D Systems Inc., Minneapolis, MN). IL-18 (Figure 7) levels were determined by specific ELISA (Medical & Biological Laboratories Co., Ltd., Nagoya, Japan). Each sample was analyzed in triplicate. Data are expressed as Mean ± SEM from 4 separate experiments using macrophages prepared from 4 separate healthy donors. These experiments established that acetylcholine dose-dependently inhibits the release of other LPS-inducible cytokines (IL-1β, IL-6 and IL-18, Figures 5, 6, and 7, respectively), but does not prevent the constitutive release of the anti-inflammatory cytokine IL-10 (Figure 8). Thus, acetylcholine specifically inhibits release of pro-inflammatory cytokines (Figures 5-7) by LPS-stimulated human macrophage cultures, but does not suppress release of the anti-inflammatory cytokine IL-10 (Figure 8). Staining with tetrazolium salt MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide, Sigma Chemical Co., St. Louis, MO), and Trypan blue exclusion of macrophage cultures treated with LPS and acetylcholine indicated that specific LPS-inducible cytokine inhibition was not due to cytotoxicity (not shown).

The molecular mechanism of acetylcholine inhibition of IL-1β and IL-6 was investigated further by measuring gene-specific mRNA levels with biotin-labeled capture oligonucleotide probes in a colorimetric microplate assay (Quantikine mRNA, R&D Systems, Inc., Minneapolis, MN). Stimulation of human macrophage cultures with LPS for 2 hours significantly increased the mRNA levels of IL-1β as compared to vehicle-treated controls (vehicle-treated IL-1β mRNA = 120 ± 54 attomole/ml vs LPS-stimulated IL-1β mRNA = 1974 ± 179 attomole/ml; n = 3; $P<0.01$). Addition of acetylcholine in concentrations (100 nM) that significantly inhibited IL-1β protein release did not significantly alter macrophage IL-1β mRNA levels (acetylcholine-treated LPS-stimulated IL-1β mRNA = 2128 ± 65 attomole/ml; n = 3). Similarly, LPS-stimulated IL-6 mRNA levels in macrophages were not significantly altered by acetylcholine concentrations that significantly inhibited IL-6 protein (LPS-stimulated IL-6 mRNA = 1716 ± 157 attomole/ml vs. acetylcholine-treated LPS-stimulated IL-6 mRNA = 1872 ± 91 attomole/ml; n = 3). Together, these observations give evidence that acetylcholine post-transcriptionally inhibits the LPS-stimulated release of TNF, IL-1β and IL-6 in macrophages.

The present results indicate that differentiated human macrophage cultures are extremely sensitive to acetylcholine and nicotine. Previous reports of cholinergic receptor activity in human peripheral blood mononuclear cells that were not differentiated into macrophages (53; 29; 46) suggested that maximal cholinergic responses required micromolar concentrations of cholinergic agonists. Our own studies establish that significantly higher concentrations of acetylcholine are required to suppress cytokine synthesis in differentiated human macrophages (acetylcholine $E.C._{50}$ for inhibiting TNF = 0.8 ± 0.2 mM, n=3). The pharmacological results now implicate an α-bungarotoxin-sensitive, nicotinic acetylcholine receptor activity that can modulate the macrophage cytokine response. This type of cholinergic receptor activity is similar to that previously described in peripheral blood mononuclear cells (53), except that macrophages are significantly more sensitive to

cholinergic agonists as compared to peripheral blood mononuclear cells. The skilled artisan would not necessarily have expected macrophages to be so sensitive to cholinergic agonists, or even have any sensitivity at all, given what was previously known with mononuclear cells. Indeed, recent evidence in our lab has revealed nicotinic receptor subunit expression patterns in macrophages that are distinct from monocytes. Therefore, the skilled artisan would understand that molecular differences underlie the greater sensitivity to cholinergic agonists of macrophages over monocytes.

Example 2

Inhibition of Endotoxic Shock by Stimulation of Efferent Vagus Nerve Fibers.

To determine whether direct stimulation of efferent vagus nerve activity might suppress the systemic inflammatory response to endotoxin, adult male Lewis rats were subjected to bilateral cervical vagotomy, or a comparable sham surgical procedure in which the vagus nerve was isolated but not transected. Efferent vagus nerve activity was stimulated in vagotomized rats by application of constant voltage stimuli to the distal end of the divided vagus nerve 10 min before and again 10 min after the administration of a lethal LPS dose (15 mg/kg, i.v.). An animal model of endotoxic shock was utilized in these experiments. Adult male Lewis rats (280-300 g, Charles River Laboratories, Wilmington, MA) were housed at 22°C on a 12 h light/dark cycle. All animal experiments were performed in accordance with the National Institute of Health Guidelines under the protocols approved by the Institutional Animal Care and Use Committee of North Shore University Hospital/ New York University School of Medicine. Rats were anesthetized with urethane (1 g/kg, intraperitoneally), and the trachea, the common carotid artery, and the jugular vein were cannulated with polyethylene tubing (Clay Adams, Parsippany, NJ). The catheter implanted into the right common carotid artery was connected to a blood pressure transducer and an Acquisition System (MP100, BIOPAC Systems,

Inc., Santa Barbara, CA) for continuous registration of mean arterial blood pressure (MABP in Figure 9). Animals were subjected to bilateral cervical vagotomy (VGX, n=7) alone or with electrical stimulation (VGX+STIM, n=7) or sham surgery (SHAM, n=7). In vagotomized animals, following a ventral cervical midline incision, both vagus trunks were exposed, ligated with a 4-0 silk suture, and divided. In sham-operated animals both vagal trunks were exposed and isolated from the surrounding tissue but not transected. Electrical stimulation of the vagus nerve was performed in animals previously subjected to vagotomy. In these groups, the distal end of right vagus nerve trunk was placed across bipolar platinum electrodes (Plastics One Inc., Roanoke, VA) connected to a stimulation module (STM100A, Harvard Apparatus, Inc., Holliston, MS) as controlled by an Acquisition System (MP100, BIOPAC Systems, Inc., Santa Barbara, CA). Constant voltage stimuli (5 V, 2 ms, 1 Hz) were applied to the nerve for 20 min (10 min before LPS administration and 10 min after). Lipopolysaccharide (*Escherichia coli* 0111:B4; Sigma Chemical Co, St. Louis, MO; 10 mg/ml in saline) was sonicated for 30 minutes, and administered at a lethal dose (15 mg/kg, i.v.). Blood was collected from the right carotid artery 1 hour after LPS administration. Serum TNF levels were quantified by the L929 bioactivity assay. To determine liver TNF levels, animals were euthanized and livers rapidly excised, rinsed of blood, homogenized by polytron (Brinkman, Westbury, NY) in homogenization buffer (PBS, containing 0.05 % sodium azide, 0.5% Triton X-100 and a protease inhibitor cocktail (2 tablets/10 ml PBS, Boehringer Mannheim, Germany); pH 7.2; 4° C), and then sonicated for 10 minutes. Homogenates were centrifuged at 12,000 g for 10 minutes, and TNF levels in supernatants determined by ELISA (Biosource International, Camarillo, CA). Protein concentrations in the supernatants were measured by the Bio-Rad protein assay (Bio-Rad Lab., Hercules, CA), and liver TNF content normalized by the amount of protein in the sample. Blood samples were collected 1 hour after LPS and TNF was measured by L929 assay. * - $P<0.05$, ** - $P<0.005$ vs. SHAM + LPS, # - $P<0.05$ vs. VGX + LPS.

As shown in Figure 9, the results establish that electrical stimulation of the efferent vagus nerve significantly attenuates peak serum TNF levels; vagotomy without electrical stimulation significantly increased peak serum TNF levels as compared to sham-operated controls ($P<0.05$).

TNF levels in liver homogenates were measured next, because liver is a principle source of peak serum TNF during endotoxemia (26; 16). Electrical stimulation of the distal vagus nerve significantly attenuated hepatic TNF synthesis as compared to sham-operated controls (Figure 10). In that figure, * - $P<0.05$ vs. SHAM + LPS, # - $P<0.05$ vs. VGX + LPS. These data directly implicate efferent vagus nerve signaling in the regulation of TNF production *in vivo*.

It was theoretically possible that electrical stimulation of the vagus nerve induced the release of humoral anti-inflammatory hormones or cytokines that inhibit TNF production. Measurements of corticosterone and IL-10 levels in sham-operated controls were performed (Table 1) to determine this.

In those studies, animals were subjected to either sham surgery (SHAM), vagotomy (VGX), or electrical stimulation with vagotomy (VGX+STIM) 30 minutes before systemic administration of LPS (15 mg/kg). Blood samples were collected 1 hour after administration of LPS or vehicle. Serum corticosterone was measured by radioimmunoassay (ICN Biomedicals, Costa Mesa, CA) and IL-10 was determined by ELISA (BioSource International, Camarillo, CA). All assays were performed in triplicate. The results are shown in Table 1, which indicates that endotoxemia was associated with increases in corticosterone and IL-10 levels. In agreement with previous studies, vagotomy significantly reduced corticosterone levels, in part because it eliminated the afferent vagus nerve signals to the brain that are required for a subsequent activation of the hypothalamic-pituitary-adrenal axis (14; 11). This decreased corticosteroid response and likely contributed to the increased levels of TNF observed in the serum and liver of vagotomized animals (Figures 9 and 10), because corticosteroids normally down-regulate TNF production (41; 39). Direct

electrical stimulation of the peripheral vagus nerve did not stimulate an increase in either the corticosteroid or the IL-10 responses. Thus, suppressed TNF synthesis in the serum and liver after vagus nerve stimulation could not be attributed to the activity of these humoral anti-inflammatory mediators.

Table 1. Effects of vagotomy and vagus nerve stimulation on serum IL-10 and corticosteroid levels during lethal endotoxemia.

Group of animals	IL-10 (ng/ml)	Corticosterone (ng/ml)
SHAM + vehicle	N.D.	160 ± 20
SHAM + LPS	8 ± 0.3	850 ± 50
Vagotomy + LPS	9 ± 0.4	570 ± 34*
Vagotomy + LPS + Stimulation	9 ± 0.5	560 ± 43*

Data shown are Mean±SEM, n=7 animals per group. * $p < 0.05$ vs. SHAM + LPS.

Figure 11 shows the results of measurement of mean arterial blood pressure (MABP) in the same groups of animals as in Figure 9 and 10 (as described in methods). Circles – sham-operated rats (SHAM), triangles – vagotomized rats (VGX), squares – animals with electrical stimulation of the vagus nerve and vagotomy (VGX + STIM). LPS (15 mg/kg, i.v.) was injected at time = 0. All data are expressed as % of MABP [MABP/MABP (at time = 0) x 100 %], Mean ± SEM; n=7. Sham-surgery, vagotomy and electrical stimulation with vagotomy did not significantly affect MABP in vehicle-treated controls (not shown).

Peripheral vagus nerve stimulation significantly attenuated the development of LPS-induced hypotension (shock) in rats exposed to lethal doses of endotoxin (Figure 11). This observation was not unexpected, because TNF is a principle early mediator of acute endotoxin-induced shock (43-44). Vagotomy alone (without electrical stimulation) significantly shortened the time to development of shock as compared to sham-operated controls (sham time to

50% drop in mean arterial blood pressure 30 ± 3 minutes versus vagotomy time to 50% drop in mean arterial blood pressure =15 ± 2 minutes; $P<0.05$). This amplified development of shock following vagotomy alone corresponded to the decreased corticosteroid response and the increased TNF response.

Acetylcholine is a vasodilator that mediates nitric oxide-dependent relaxation of resistance blood vessels which causes a decrease in blood pressure. Thus, we wished to exclude the possibility that stimulation of the efferent vagus might have mediated a paradoxical hypertensive response. Hypertension was not observed following vagus nerve stimulation of controls given saline instead of endotoxin (not shown), indicating that protection against endotoxic shock by vagus nerve stimulation is specific. Considered together, these observations indicate that stimulation of efferent vagus nerve activity downregulates systemic TNF production and the development of shock during lethal endotoxemia.

Example 3

Stimulation of Intact Vagus Nerve Attenuates Endotoxic Shock.

Experiments were conducted to determine whether the inhibition of inflammatory cytokine cascades by efferent vagus nerve stimulation is effective by stimulation of an intact vagus nerve. Stimulation of left and right vagus nerves were also compared.

The vagus nerves of anesthetized rats were exposed, and the left common iliac arteries were cannulated to monitor blood pressure and heart rate. Endotoxin (*E. Coli* 0111:B4; Sigma) was administered at a lethal dose (60 mg/kg). In treated animals, either the left or the right intact vagus nerve was stimulated with constant voltage (5V or 1V, 2 ms, 1 Hz) for a total of 20 min., beginning 10 min. before and continuing 10 min. after LPS injection. Blood pressure and heart rate were through the use of a Bio-Pac M100 computer-assisted acquisition system. Figures 12-14 show the results of these experiments.

As shown in Figure 12, within minutes after LPS injection, the blood pressure began to decline in both unstimulated rats and rats treated with a low dose (1V) of vagus nerve stimulation, while rats treated with a high dose (5V) of stimulation maintained more stable blood pressures. Between 30 and 40 min. post-LPS, the blood pressure stabilized in animals treated with a low dose of voltage.

Figure 13 shows the heart rate of the experimental animals. Within minutes after LPS injection, the heart rate began to increase in rats stimulated with a high dose (5V) of vagus nerve stimulation. On the other hand, the heart rates of both unstimulated rats and rats stimulated with a low dose (1V) of voltage remained stable for approximately 60 min. post-LPS. After one hour, the heart rates of the rats treated with a low dose of stimulation began to increase, and reached levels comparable to those rats receiving a high dose of vagus nerve stimulation.

Figure 14 compares left vs. right vagus nerve stimulation. Endotoxic animals were treated with 1V stimulation in either the left or the right vagus nerve. Within minutes after LPS injection, the blood pressure began to decline in all three stes of animals (unstimulated, left stimulation, right stimulation). Though both sets of stimulated animals recovered blood pressure, those animals receiving stimulation in the left vagus nerve maintained more stable blood pressures for the duration of the experiment. However, the difference in results between left and right vagus nerve stimulation was not statistically significant, and would not be expected to have any practical difference.

This set of experiments confirms that stimulation of an intact vagus nerve can effectively inhibit an inflammatory cytokine cascade sufficiently to alleviate conditions caused by the cascade.

Example 4

Inhibition of Hmg-1 Release from Macrophages by Nicotine.

Experiments were performed to determine whether the inhibitory effect of cholinergic agonists on proinflammatory cytokines applied to HMG-1. Murine RAW 264.7 macrophage-like cells (American Type Culture Collection, Rockville, MD, USA) were grown in culture under DMEM supplemented with 10% fetal bovine serum and 1% glutamine. When the cells were 70-80% confluent, the medium was replaced by serum-free OPTI-MEM I medium. Nicotine (Sigma) was then added at 0, 0.1, 1, 10 or 100 μM. Five minutes after adding the nicotine, the cultures were treated with LPS (500 ng/ml). Culture medium was collected after 20 hr. The culture medium was concentrated with a Centricon™. 10 filter, then analyzed by western blot, using an anti-HMG-1 polyclonal antisera (WO 00/47104) and standard methods. Band densities were determined using a Bio-Rad Imaging densitometer.

The results are shown in Figure 15. The HMG-1 bands are shown along the top, with the corresponding nicotine and LPS concentrations, and the densities of the bands shown are graphed in the graph below. Figure 15 clearly shows that nicotine inhibited HMG-1 production in a dose-dependent manner. This demonstrates that HMG-1 behaves as a proinflammatory cytokine in that its production can be inhibited by a cholinergic agonist.

The neural-immune interaction described here, which we term the "cholinergic anti-inflammatory pathway," can directly modulate the systemic response to pathogenic invasion. The observation that parasympathetic nervous system activity influences circulating TNF levels and the shock response to endotoxemia has widespread implications, because it represents a previously unrecognized, direct, and rapid endogenous mechanism that can be activated to suppress the lethal effects of biological toxins. The cholinergic anti-inflammatory pathway is positioned to function under much shorter response times as compared to the previously described humoral anti-inflammatory

pathways. Moreover, activation of parasympathetic efferents during systemic stress, or the "flight or fight" response, confers an additional protective advantage to the host by restraining the magnitude of a potentially lethal peripheral immune response.

In view of the above, it will be seen that the several advantages of the invention are achieved and other advantages attained.

As various changes could be made in the above methods and compositions without departing from the scope of the invention, it is intended that all matter contained in the above description and shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

References Cited

1. Antonica, A., *et al.*, *J. Auton. Nerv. Syst.*, 48:187-97, 1994.

2. Besedovsky, H., et al., *Science*, 233:652-54, 1986.

3. Blackwell, T.S., and Christman, J.W., *Br. J. Anaesth.*, 77: 110-17, 1996.

4. Blum, A. and Miller, H., *Am. Heart J.*, 135:181-86, 1998.

5. Borovikova, L.V., *et al.*, *Nature*, 405: 458-62, 2000a.

6. Borovikova, L.V., *et al.*, *Auton. Neurosci.*, 20:141-47, 2000b.

7. Bumgardner, G.L., and Orosz, C.G., *Semin. Liver Dis.*, 19: 189-204, 1999.

8. Carteron, N.L., *Mol. Med. Today*, 6:315-23, 2000.

9. Dibbs, Z., *et al.*, *Proc. Assoc. Am. Physicians*, 111:423-28, 1999.

10. Dinarello, C.A., *FASEB J.*, 8:1314-25, 1994.

11. Fleshner, M., *et al.*, *J. Neuroimmunol.*, 86:134-41, 1998.

12. Fox, D.A., *Arch. Intern. Med.*, 28:437-444, 2000.

13. Gattorno, M., *et al., J. Rheumatol.,* 27:2251-2255, 2000.

14. Gaykema, R.P., *et al., Endocrinology,* 136:4717-4720, 1995.

15. Gracie, J.A., *et al., J. Clin. Invest.,* 104:1393-1401, 1999.

16. Gregory, S.H. and Wing, E.J., *Immunology Today,* 19:507-10, 1998.

17. Guslandi, M., *Br. J. Clin. Pharmacol.,* 48:481-84, 1999.

18. Hirano, T., *J. Surg. Res.,* 81:224-29, 1999.

19. Hommes, D.W. and van Deventer, S.J., *Curr. Opin. Clin. Nutr. Metab. Care, 3*:191-95, 2000.

20. Hsu, H.Y., *et al., J. Pediatr. Gastroenterol.,* 29:540-45, 1999.

21. Hu, X.X., *et al., J. Neuroimmunol.,* 31:35-42, 1991.

22. Jander, S. and Stoll, G., *J. Neuroimmunol.,* 114:253-58, 2001.

23. Kanai, T. *et al., Digestion,* 63 Suppl. 1:37-42, 2001.

24. Katagiri, M., *et al., J. Clin, Gastroenterol.,* 25 Suppl. 1: S211-14, 1997.

25. Kimmings, A.N., *et al., Eur. J. Surg.,* 166:700-05, 2000.

26. Kumins, N.H., *et al., SHOCK,* 5:385-88, 1996.

27. Lee, H.G., *et al., Clin. Exp. Immunol.,* 100:139-44, 1995.

28. Lipton, J.M. and Catania, A., *Immunol. Today,* 18:140-45, 1997.

29. Madretsma, G.S., *et al., Immunopharmacology,* 35:47-51, 1996.

30. McGuinness, P.H., *et al., Gut,* 46:260-69, 2000.

31. Nathan, C.F., *J. Clin. Invest.,* 79:319-26, 1987.

32. Pulkki, K.J., *Ann. Med.,* 29:339-43, 1997.

33. Prystowsky, J.B. and Rege, R.V., *J. Surg. Res.,* 71;123-26 1997.

34. Rayner, S.A. *et al., Clin. Exp. Immunol.,* 122:109-16, 2000.

35. Romanovsky, A.A., *et al., Am. J. Physiol.,* 273:R407-13, 1997.

36. Sandborn, W.J., *et al., Ann. Intern. Med,* 126:364-71, 1997.

37. Sato, E., *et al., Am. J. Physiol.,* 274:L970-79, 1998.

38. Sato, K.Z., *et al., Neurosci. Lett.,* 266:17-20, 1999.

39. Scheinman, R.I., *et al., Science,* 270:283-86, 1995.

40. Sher, M.E., *et al., Inflamm. Bowel Dis.,* 5:73-78, 1999.

41. Sternberg, E.M., *J. Clin. Invest.,* 100:2641-47, 1997.

42. Thompson, A., Ed. *The Cytokine Handbook, 3rd ed.,* Academic Press, 1998.

43. Tracey, K.J. *et al., Nature,* 330:662-64, 1987.

44. Tracey, K.J. *et al., Science,* 234:470-74, 1986.

45. Tsutsui, H., *et al., Immunol. Rev.,* 174:192-209, 2000.

46. van Dijk, A.P., *et al., Eur. J. Clin. Invest.,* 28:664-71, 1998.

47. Wang, H., *et al., Science,* 285:248-51, 1999.

48. Waserman, S., *et al., Can. Respir. J.,* 7:229-37, 2000.

49. Watanabe, H. *et al., J. Reconstr. Microsurg.,* 13:193-97, 1997.

50. Wathey, J.C., *et al., Biophys. J.,* 27:145-64, 1979.

51. Watkins, L.R. and Maier, S.F., *Proc. Natl. Acad. Sci. U. S. A.,* 96:7710-13, 1999.

52. Watkins L.R., *et al., Neurosci. Lett.* 183:27-31, 1995.

53. Whaley, K., *et al., Nature,* 293:580-83, 1981.

54. Woiciechowsky, C., *et al., Nat. Med.,* 4: 808-13, 1998.

55. Yeh, S.S., and Schuster, M.W., *Am. J. Clin. Nutr.*, 70, 183-97, 1999.

56. Zhang and Tracey, in *The Cytokine Handbook, 3rd ed.*, Ed. Thompson, Academic Press, 515-47, 1998.

57. PCT patent publication WO 00/47104.

58. Sambrook, *et al.*, *Molecular Cloning: A Laboratory Manual*, Cold Spring Harbor Laboratory Press, 1989.

All references cited in this specification are hereby incorporated by reference. The discussion of the references herein is intended merely to summarize the assertions made by the authors and no admission is made that any reference constitutes prior art. Applicants reserve the right to challenge the accuracy and pertinence of the cited references.

What is claimed is:

1. A method of inhibiting the release of a proinflammatory cytokine from a mammalian cell, the method comprising treating the cell with a cholinergic agonist in an amount sufficient to decrease the amount of the proinflammatory cytokine that is released from the cell, wherein the cell is a macrophage.

2. The method of claim 1, wherein the proinflammatory cytokine is selected from the group consisting of tumor necrosis factor (TNF), interleukin (IL)-1β, IL-6, IL-18 and HMG-1.

3. The method of claim 1, wherein the proinflammatory cytokine is TNF.

4. The method of claim 1, wherein the cholinergic agonist is selected from the group consisting of acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, and levamisole.

5. The method of claim 1, wherein the cell is in a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade.

6. The method of claim 5, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis,

cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza,respiratory syncytial virus infection, herpes infection, HIV infection, hepatitis B virus infection, hepatitis C virus infection, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, and Hodgkins disease.

7. The method of claim 6, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection and graft-versus-host disease.

8. The method of claim 6, wherein the condition is endotoxic shock.

9. The method of claim 6, wherein the treatment with the cholinergic agonist is effected by stimulating efferent vagus nerve activity sufficient to inhibit the inflammatory cytokine cascade.

10. The method of claim 9, wherein efferent vagus nerve activity is stimulated electrically.

11. The method of claim 9, wherein afferent vagus nerve fibers are not stimulated.

12. The method of claim 9, wherein ganglions or postganglionic neurons are stimulated.

13. The method of claim 9, wherein peripheral tissues or organs served by the vagus nerve are stimulated directly.

14. A method of inhibiting an inflammatory cytokine cascade in a patient, comprising treating the patient with a cholinergic agonist in an amount sufficient to inhibit the inflammatory cytokine cascade, wherein the patient is suffering from, or at risk for, a condition mediated by the inflammatory cytokine cascade.

15. The method of claim 14, wherein the cholinergic agonist is selected from the group consisting of acetylcholine, nicotine, muscarine, carbachol, galantamine, arecoline, cevimeline, and levamisole.

16. The method of claim 14, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers,

peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis, cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza, respiratory syncytial virus infection, herpes infection, HIV infection, hepatitis B virus infection, hepatitis C virus infection, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, and Hodgkins disease.

17. The method of claim 16, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ

ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection and graft-versus-host disease.

18. The method of claim 18, wherein the condition is endotoxic shock.

19. The method of claim 14, wherein the treatment with the cholinergic agonist is effected by stimulating efferent vagus nerve activity.

20. The method of claim 19, wherein efferent vagus nerve activity is stimulated electrically.

21. The method of claim 19, wherein afferent vagus nerve fibers are not stimulated.

22. The method of claim 19, wherein ganglions or postganglionic neurons are stimulated.

23. The method of claim 19, wherein peripheral tissues or organs served by the vagus nerve are stimulated directly.

24. A method for treating a patient suffering from, or at risk for, a condition mediated by an inflammatory cytokine cascade, the method comprising stimulating efferent vagus nerve activity of the patient sufficient to inhibit the inflammatory cytokine cascade.

25. The method of claim 24, wherein the vagus nerve activity is stimulated electrically.

26. The method of claim 24, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers, peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, diverticulitis, epiglottitis, achalasia, cholangitis, cholecystitis, hepatitis, Crohn's disease, enteritis, Whipple's disease, asthma, allergy, anaphylactic shock, immune complex disease, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, shock, cachexia, hyperpyrexia, eosinophilic granuloma, granulomatosis, sarcoidosis, septic abortion, epididymitis, vaginitis, prostatitis, urethritis, bronchitis, emphysema, rhinitis, cystic fibrosis, pneumonitis, pneumoultramicroscopicsilicovolcanoconiosis, alvealitis, bronchiolitis, pharyngitis, pleurisy, sinusitis, influenza, respiratory syncytial virus infection, herpes infection, HIV infection, hepatitis B virus infection, hepatitis C virus infection, disseminated bacteremia, Dengue fever, candidiasis, malaria, filariasis, amebiasis, hydatid cysts, burns, dermatitis, dermatomyositis, sunburn, urticaria, warts, wheals, vasulitis, angiitis, endocarditis, arteritis, atherosclerosis, thrombophlebitis, pericarditis, myocarditis, myocardial ischemia, periarteritis nodosa, rheumatic fever, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, meningitis, encephalitis, multiple sclerosis, cerebral infarction, cerebral embolism, Guillame-Barre syndrome, neuritis, neuralgia, spinal cord injury, paralysis, uveitis, arthritides, arthralgias, osteomyelitis, fasciitis, Paget's disease, gout, periodontal disease, rheumatoid arthritis, synovitis, myasthenia gravis, thryoiditis, systemic lupus erythematosus, Goodpasture's syndrome, Behcets's syndrome, allograft rejection, graft-versus-host disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Type I diabetes, ankylosing spondylitis, Berger's disease, Retier's syndrome, and Hodgkins disease.

27. The method of claim 26, wherein the condition is selected from the group consisting of appendicitis, peptic, gastric and duodenal ulcers,

peritonitis, pancreatitis, ulcerative, pseudomembranous, acute and ischemic colitis, hepatitis, Crohn's disease, asthma, allergy, anaphylactic shock, organ ischemia, reperfusion injury, organ necrosis, hay fever, sepsis, septicemia, endotoxic shock, cachexia, septic abortion, disseminated bacteremia, burns, Alzheimer's disease, coeliac disease, congestive heart failure, adult respiratory distress syndrome, cerebral infarction, cerebral embolism, spinal cord injury, paralysis, allograft rejection and graft-versus-host disease.

28. The method of claim 26, wherein the condition is endotoxic shock.

29. The method of claim 24, wherein afferent vagus nerves are not stimulated.

30. The method of claim 24, wherein ganglions or postganglionic neurons are stimulated.

31. The method of claim 24, wherein peripheral tissues or organs served by the vagus nerve are stimulated directly.

32. A method for attenuation of a systemic inflammatory response to endotoxin in a patient, comprising stimulating efferent vagus nerve activity of the patient sufficient to inhibit an inflammatory cytokine cascade.

33. A method for determining whether a compound is a cholinergic agonist, the method comprising determining whether the compound inhibits the release of a proinflammatory cytokine from a mammalian cell.

34. The method of claim 33, wherein the cell is a macrophage.

35. The method of claim 33, wherein the proinflammatory cytokine is TNF.

FIGURE 1

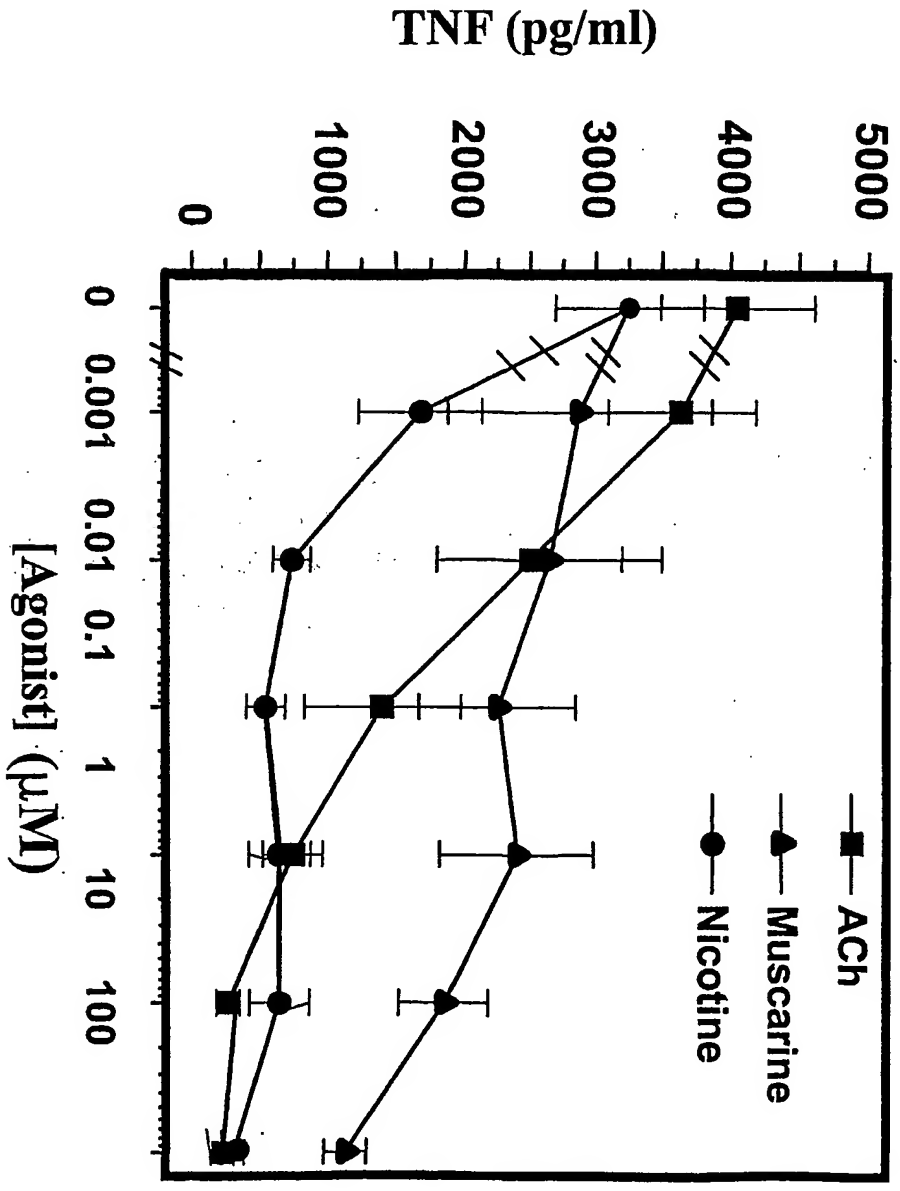


FIGURE 2

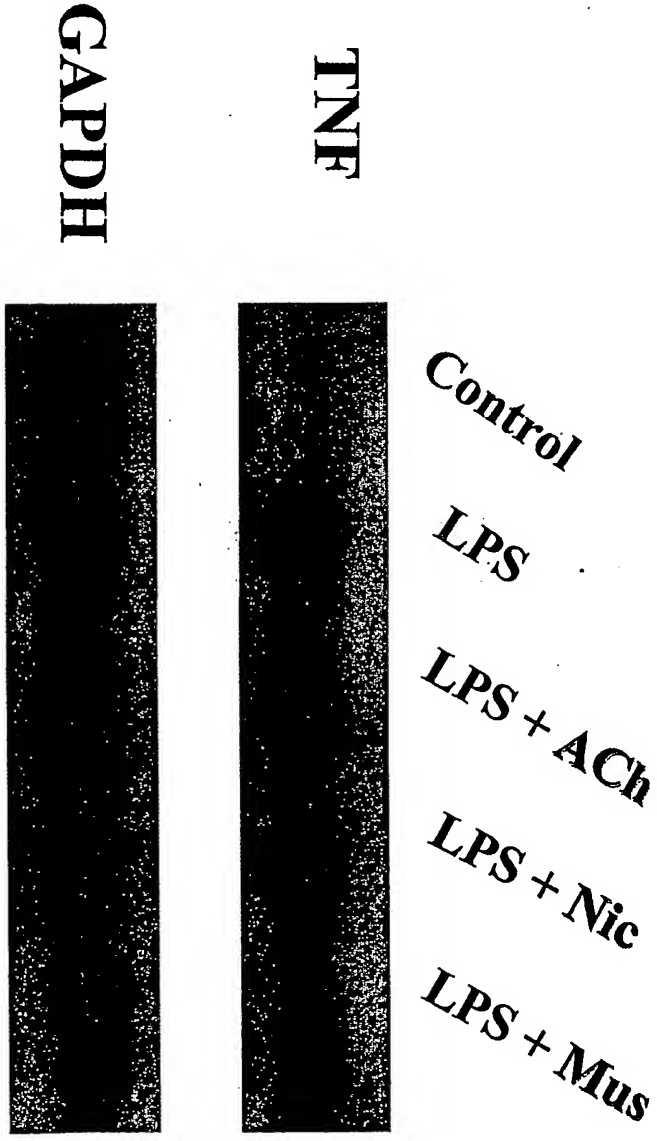


FIGURE 3

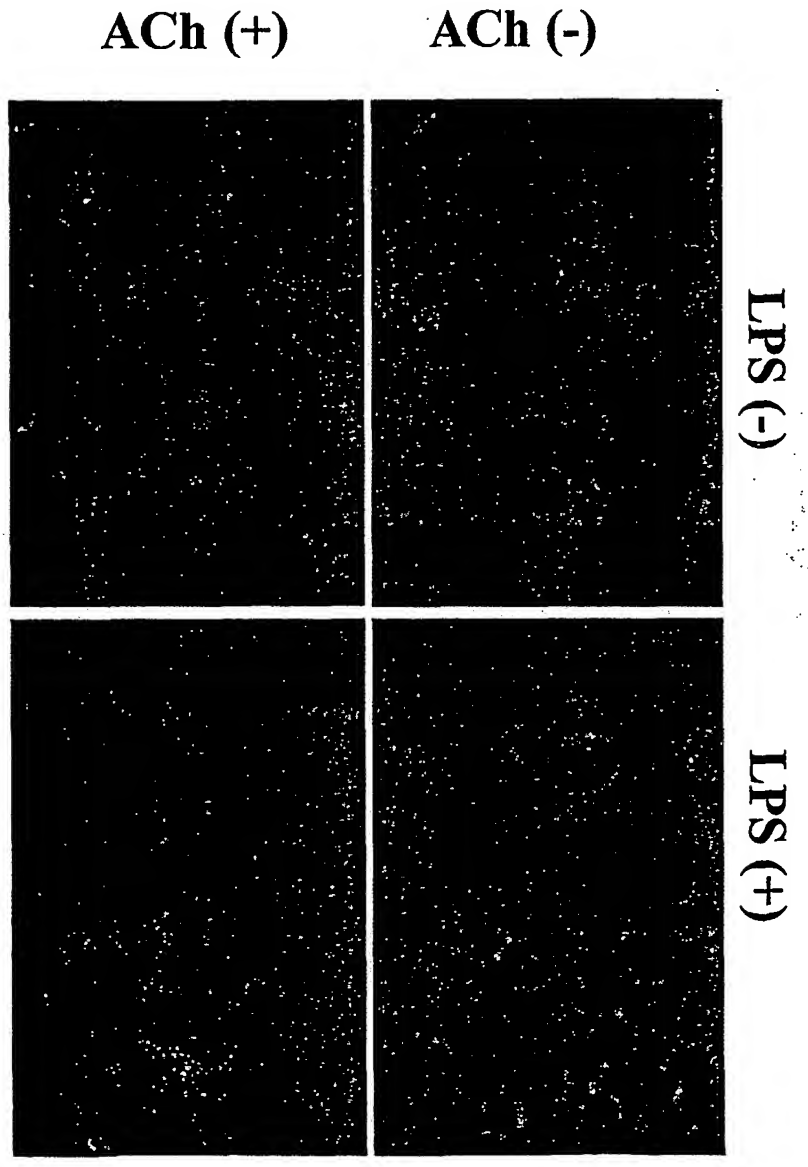


FIGURE 4

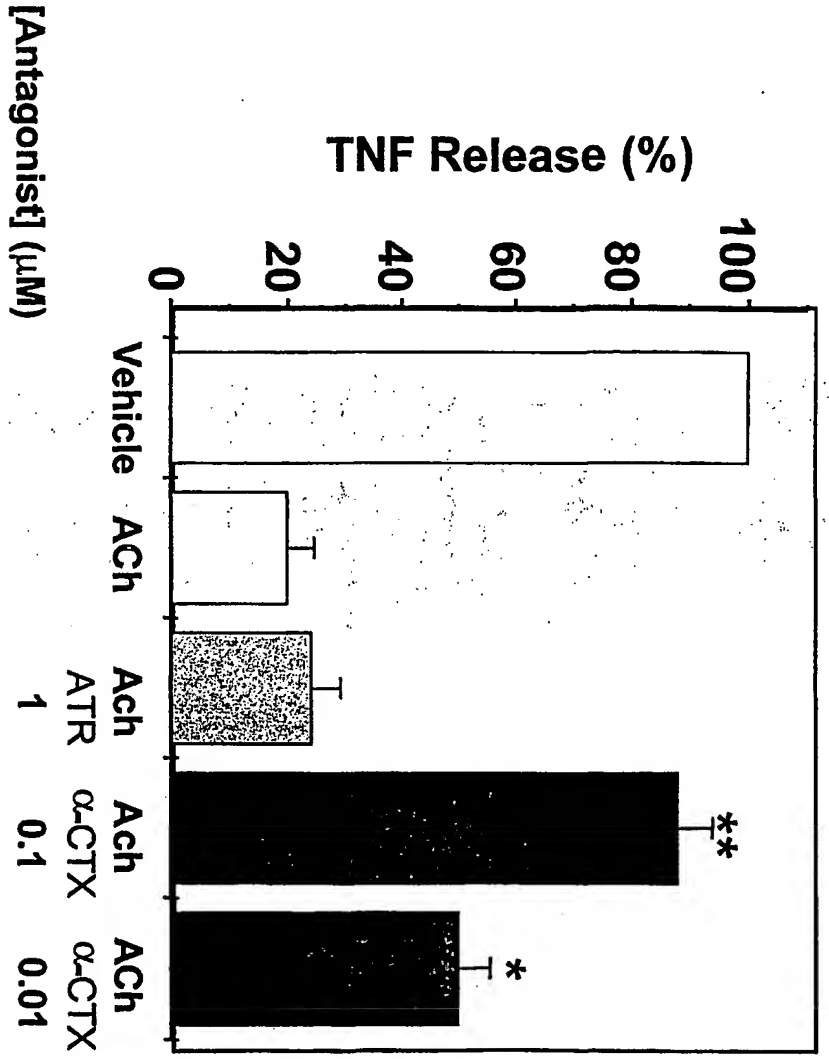

TNF Release (%)
0
20
40
60
80
100
[Antagonist] (μM)
Vehicle
ACh
ACh ATR 1
ACh α-CTX 0.1
ACh α-CTX 0.01
**
*

FIGURE 5

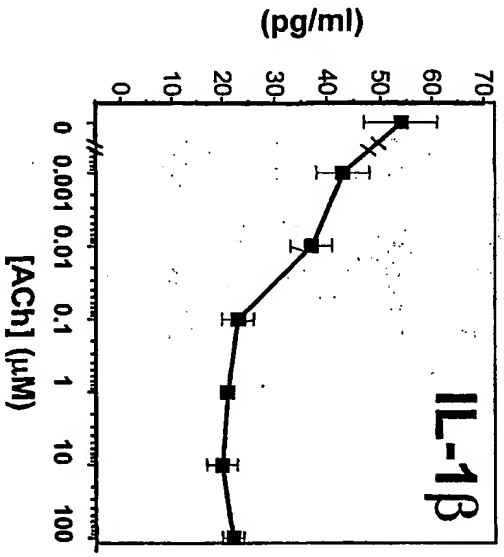


FIGURE 6

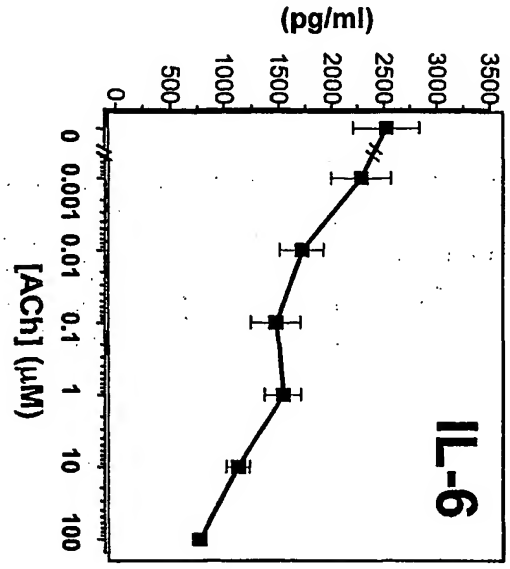

(pg/ml)
0
500
1000
1500
2000
2500
3000
3500
[ACh] (μM)
0
0.001
0.01
0.1
1
10
100
IL-6

FIGURE 7

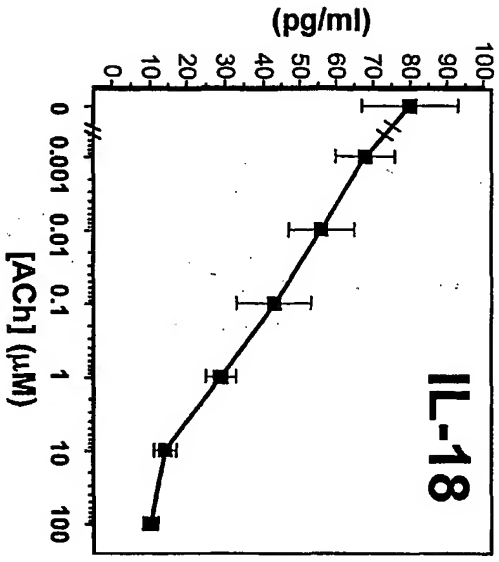


FIGURE 8

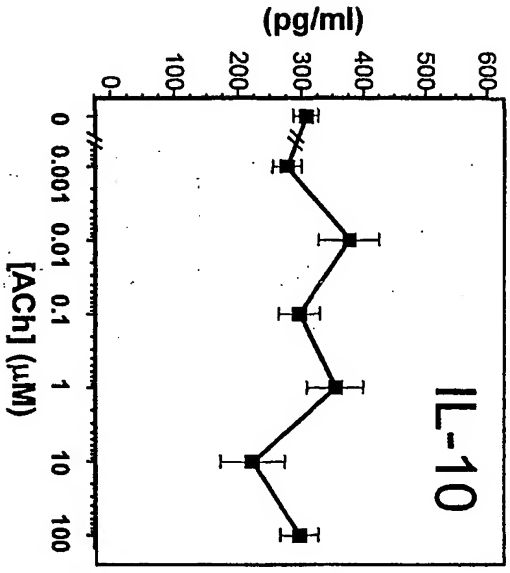


FIGURE 9

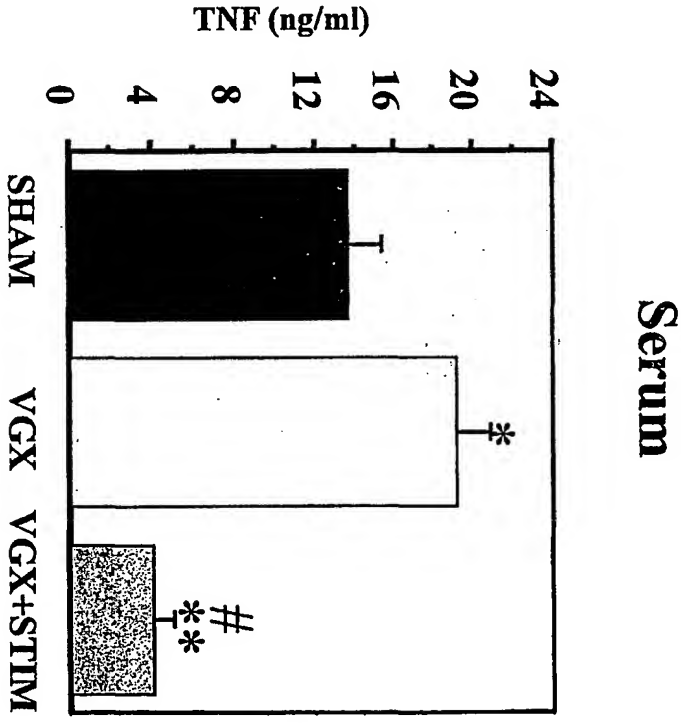


FIGURE 10

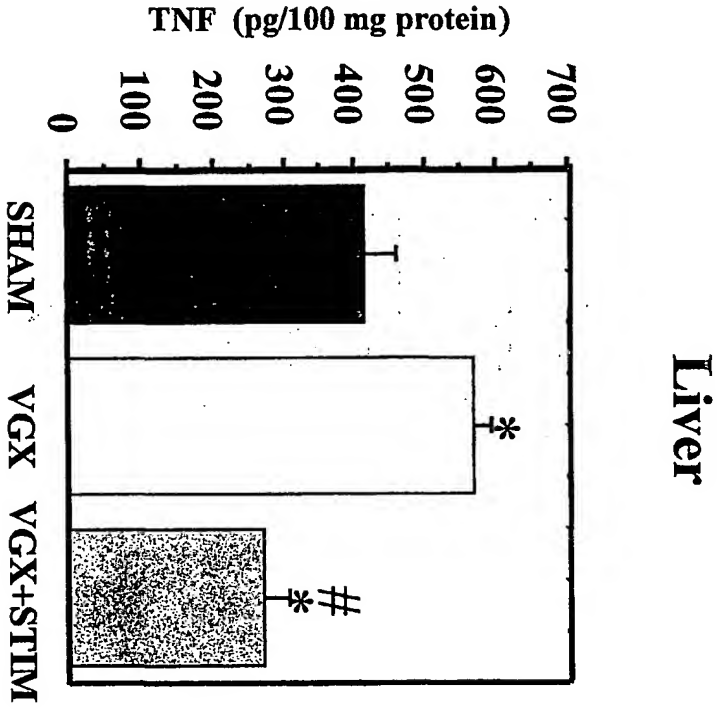

TNF (pg/100 mg protein)
0
100
200
300
400
500
600
700
SHAM
VGX
VGX+STIM
*
*
#
Liver

FIGURE 11

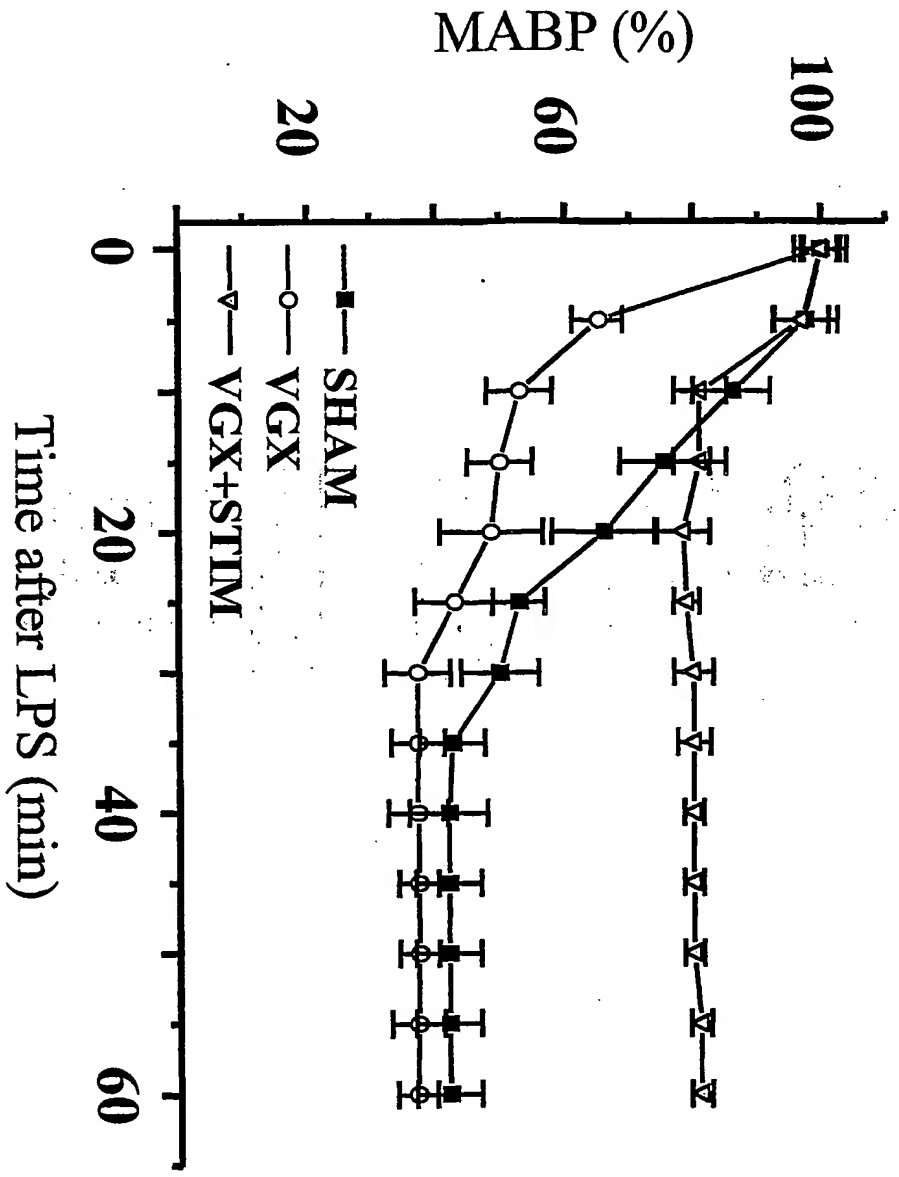


FIGURE 12

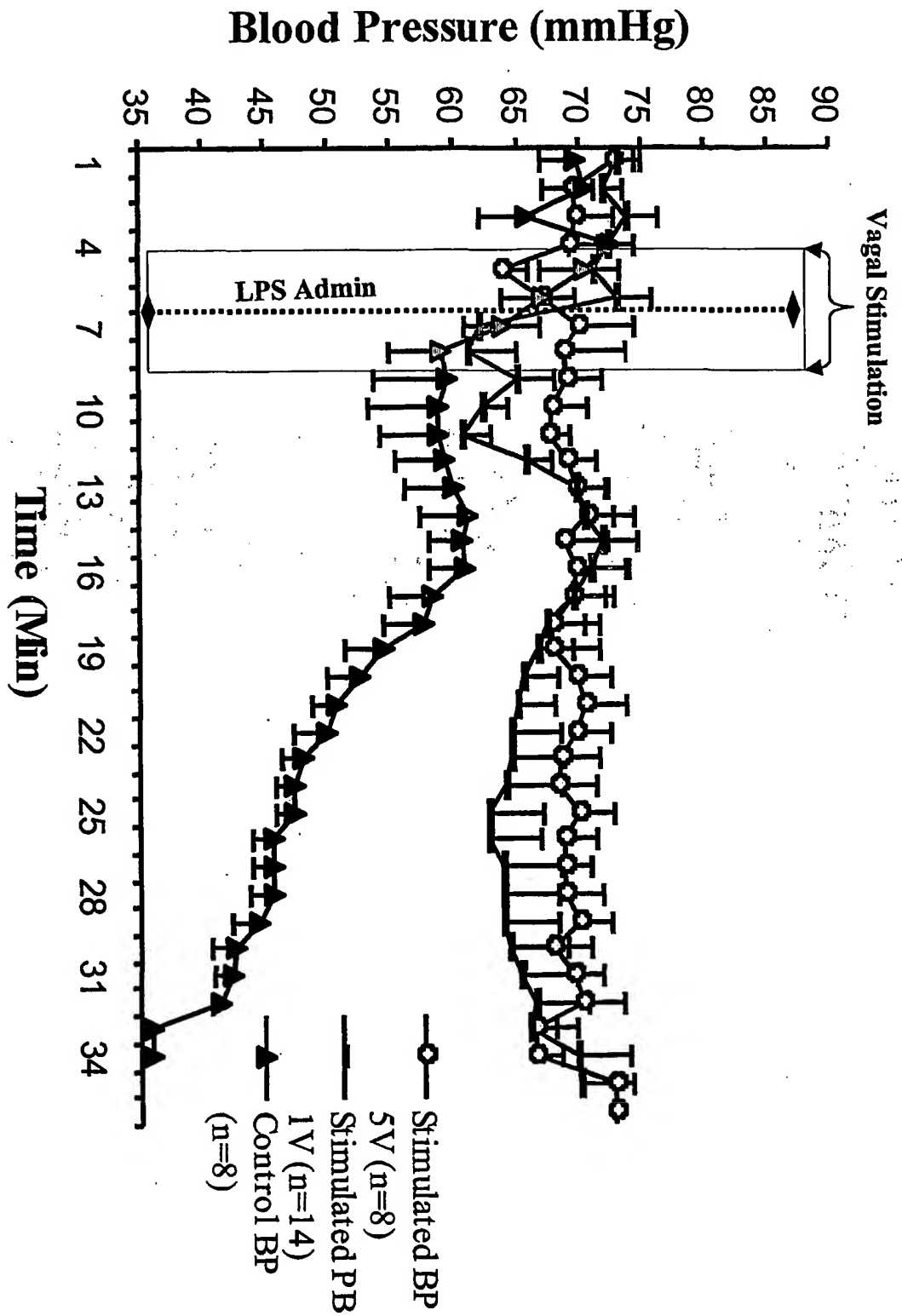


FIGURE 13

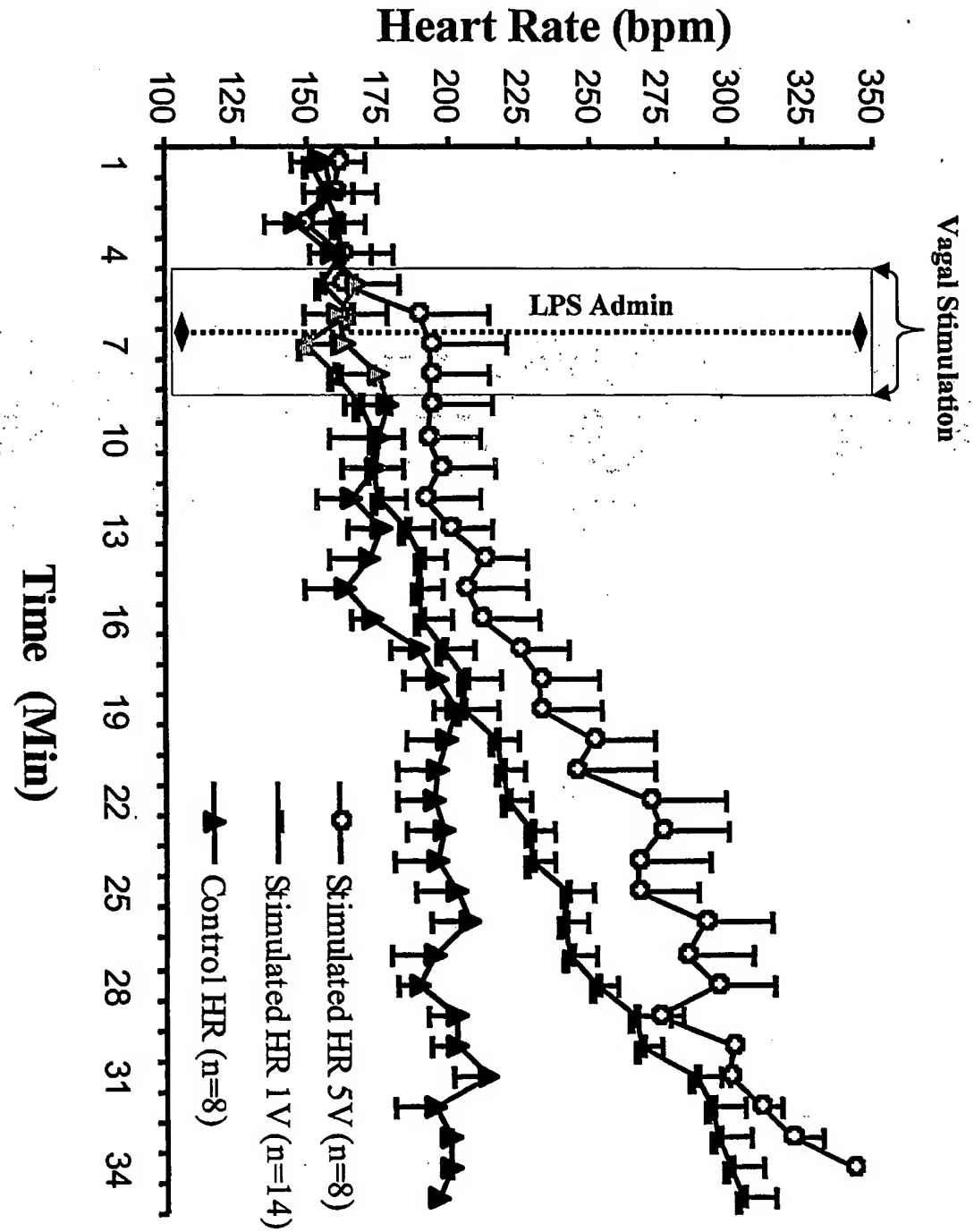


FIGURE 14

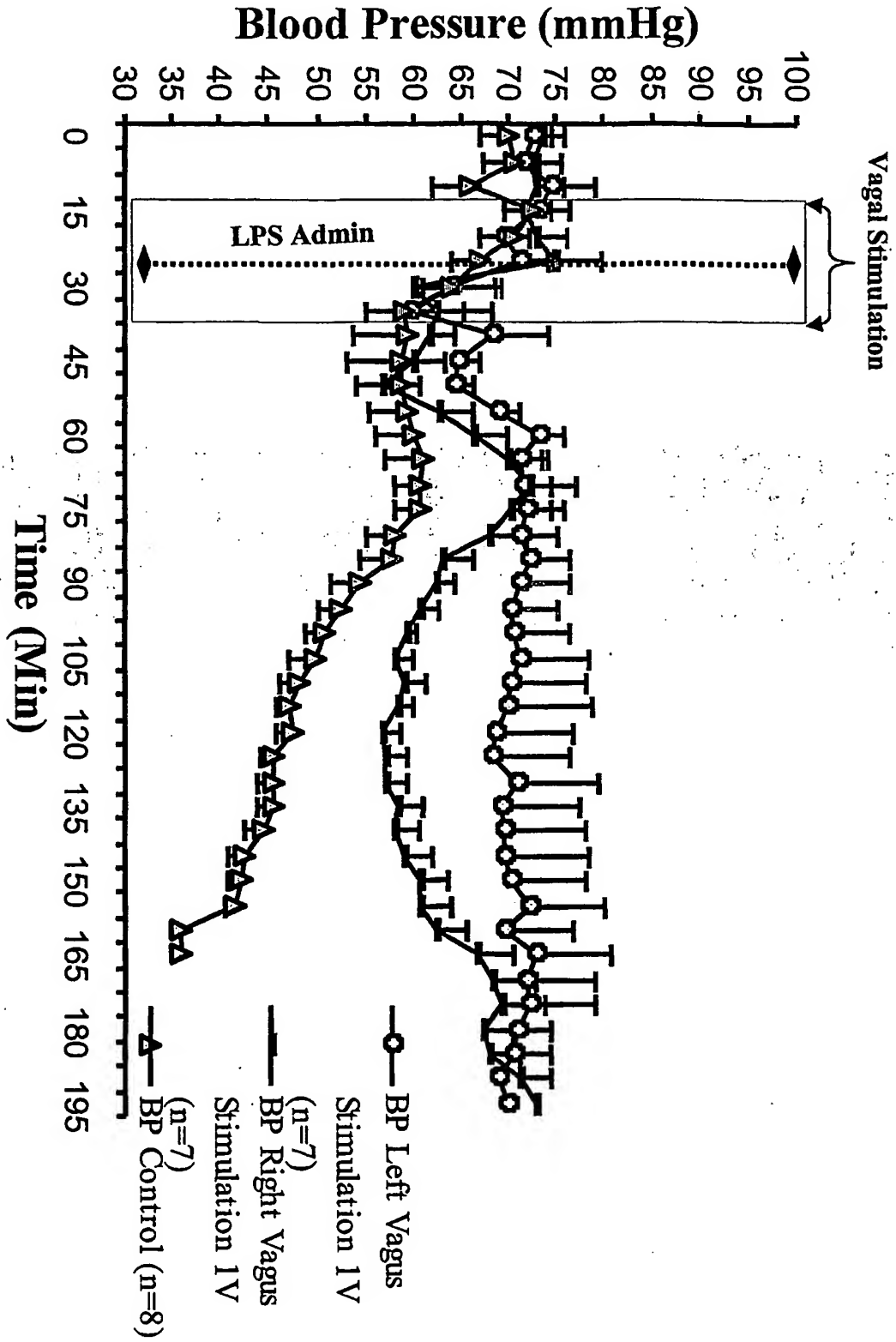
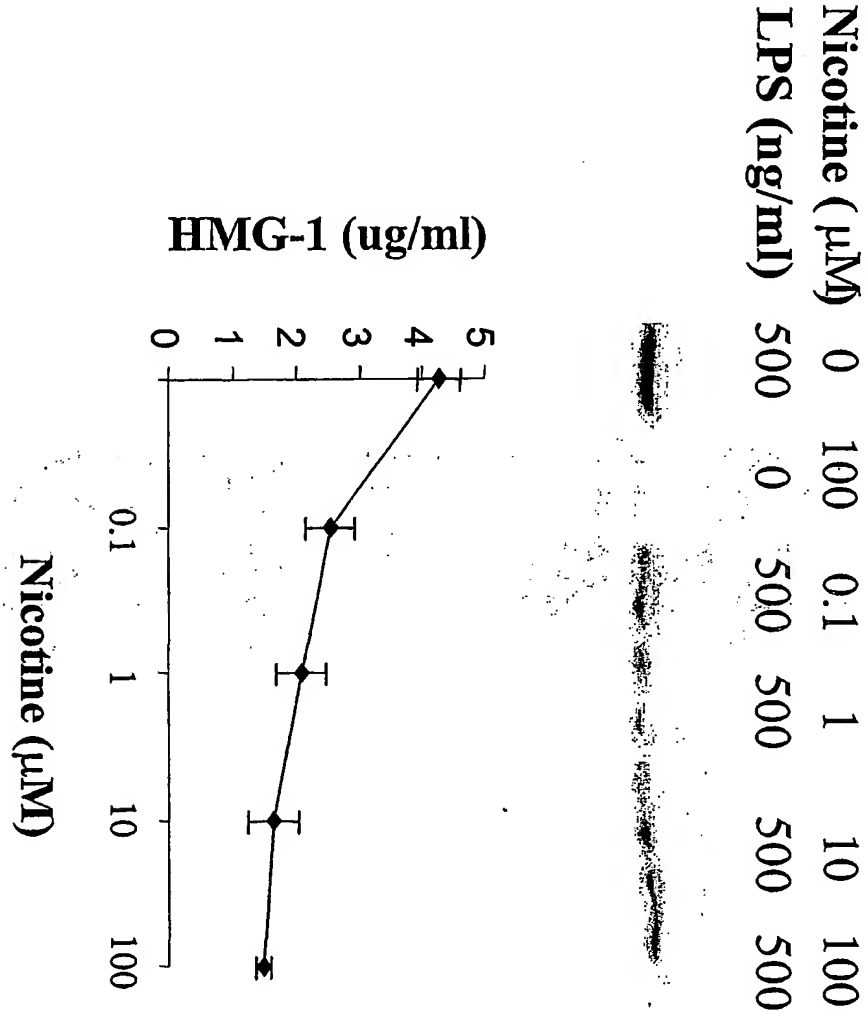


FIGURE 15


HMG-1 (ug/ml)
0
1
2
3
4
5
0.1
1
10
100
Nicotine (μM)
Nicotine (μM) 0 100 0.1 1 10 100
LPS (ng/ml) 500 0 500 500 500 500

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/15708

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) :A61K 31/44
US CL :514/343, 356, 449, 473, 213.01, 216
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 514/343, 356, 449, 473, 213.01, 216

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A, P	US 6,096,728 A (COLLINS et al.) 1 August 2000, see entire document.	1-35
Y	US 5,733,255 A (DINH et al.) 31 March 1998, see col. 10, lines 49-51.	1-23, 33-35
X	US 5,567,724 A (KELLEHER, et al.) 22 October 1996, see Examples 7 and 9.	1-7, 14-17
Y	US 5,709,853 A (IINO et al.) 20 January 1998, see col. lines 34-35.	1-23, 33-35
Y	US 5,604,231 A (SMITH et al.) 18 February 1997, see col. 2, lines 9-16.	1-23, 33-35

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search	Date of mailing of the international search report
15 JUNE 2001	06 NOV 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer Cybille Delacroix-Muirheid Telephone No. (703) 308-0196

Form PCT/ISA/210 (second sheet) (July 1998) ★

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US01/15708

B. FIELDS SEARCHED
Electronic data bases consulted (Name of data base and where practicable terms used):

EAST
inflammation, cytokine, interferon, TNF, endotoxic shock, ulcer, alzheimer's, peritonitis, asthma, muscarine, arecoline, acetylcholine, nicotine, carbachol, galanthamine, cevimeline